underneath become invalid. A possible solution to this problem will be molecular or atomic layer deposition.[8]

(3) Finally, the electrodes are still not fully compact (ordered pores of 500 μm width) and thus have a low material density. This makes the volumetric energy density of the assembled full cells not competitive—approximately 0.2 Wh L^{-1} for both 8-mm-thick and 2-mm-thick devices. This is in contrast to the symmetric supercapacitors made from 0.4-mm-thick highly compact graphene pallet electrodes (device thickness ~1 mm), which gives a volumetric energy density of 65 Wh L^{-1}.[9]

Overall, this work is technologically very inspiring and represents significant progress in achieving high areal-, volumetric-, and gravimetric-capacitance supercapacitors with unprecedentedly high mass loading of pseudocapacitive materials. It also provides a nice manifestation on how to optimize the fundamental electrochemistry process (mass transport, ion diffusion, etc.) by tailoring the electrode architecture. The 3D-printing technology creates a fascinating avenue for the energy domain. More opportunities include conductive polymer and 2D materials for energy storage, photoelectrodes for solar fuels, electrocatalytic materials for water splitting, and metal-air batteries.

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Preview

Power Shortfalls in the Wake of Climate Change

Brandon R. Sutherland[1,*]

Increasing global mean temperatures and shifting weather patterns due to anthropogenic climate change will influence the supply and demand of electricity. Recently in *Nature Communications*, Turner and colleagues predicted the impact of current climate change models on the risks of electric grid power shortfalls in the U.S. Pacific Northwest.

The electric grid is the backbone of on-demand access to energy in the digital age. It comprises a series of generators that deliver power through a transmission system to end users. Regardless of the time of day, society demands access to electricity to watch television, use computers, have meetings in brightly lit offices, or excessively mine cryptocurrency.[1] Maintaining an electric grid with minimal disruptions, such as power shortfalls and blackouts, is a challenging task. Power shortfall occurs when the supply of electricity cannot meet the demand, often because of unexpected and sudden environmental events. To avoid this without incurring significant operational overhead, electric power companies employ complex predictive models to ensure resiliency.[2] Through these efforts, modern societies have access to a seemingly unlimited amount of uninterrupted energy for their daily needs—and well beyond.

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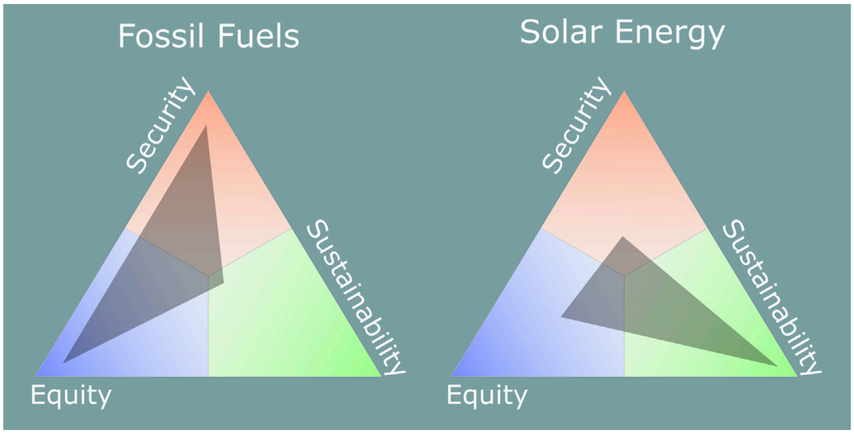

Figure 1. The Energy Trilemma for Solar and Fossil Fuels

To maintain grid resiliency as the global environmental landscape shifts due to climate change, it is important to develop improved predictors for power grid management. High confidence models of climate change still predict global temperature increases of 1.5°C between 2030 and 2052 at current rates.[3] This is coupled with expected increases in the frequency of natural disasters, and precipitation extremes. Examining the effects of various climate models on the electric power system is an ongoing area of research. At present, existing studies focus on climate-induced changes in the operation and resiliency of a single element of the power system (supply[4] or demand[5]). However, to better inform electric power policy, the effects of these changes on the entire power system must be examined holistically.

Recently in *Nature Communications*, Turner and colleagues have modeled and forecasted the compound impacts of climate change on the power system in the U.S. Pacific Northwest for the year 2035.[6] They evaluate the risk of power shortfall under six scenarios from a combination of regional infrastructure development and climate change predictors. Using a previously reported power system model with hourly resolution,[7] they show a significant transformation on the power shortfall frequency, duration, and timing under conservatively estimated climate change conditions for the region based on INMCM4.0[8] and GFDL-ESM2M[9] models.

The Pacific Northwest in the U.S. has variable weather conditions and a diversified electricity supply, making it a model region for climate change impact studies. It has distinct seasons, from hot summer months to colder winters with snow. Its electricity system relies heavily on hydroelectric dams, providing near 50% of the annual generation capacity. The rest is supplied by natural gas, coal, and renewables (predominantly wind). The peak load on the electric grid typically occurs during cold winter days, which is attributed to large increases in building heating, and hot summer days for increased building cooling.

Evaluating the influence of climate-changed induced temperature and precipitation variations on an electric grid model reveals several key findings. It is observed that by 2035, the number of annual power shortfalls under climate change will increase; however, their duration will decrease, lasting about half as long from 13 ± 1 to ~7 ± 1 h, and their intensity will decrease, with an average maximum loss of 400 MW, down from 1,000 MW. The timing of these events will further see a large shift from winter months to summer months. Approximately 50% of the associated risk increase is due to the compound effects of increased power demand and reduced hydroelectric availability coinciding in the summer months, highlighting the importance of considering the entire integrated power system in predictive modeling.

Taking these findings together, a curious observation is made that climate change "may therefore be viewed as both a risk and an opportunity for power system performance."[6] The details of this tradeoff will be heavily determined by the specific energy and environmental landscape of a given region. No single energy system is highly resilient, cost competitive, and has a low-carbon footprint. This results in an "energy trilemma" between security, equity, and sustainability.[10] Global trends for new energy capacity additions are largely renewable based. At present, renewable energy, such as photovoltaics, is typically less resilient and more expensive than fossil fuels, despite its low-carbon emissions life cycle (Figure 1). With much of the expected growth around the globe to occur by subtracting "reliable" fossil fuels and adding renewables, the issue of energy security becomes more prominent and more compound studies in the wake of climate change are urgently needed.

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Preview

Li-O_2 Cell-Scale Energy Densities

Christian Prehal[1] and Stefan A. Freunberger[1,*]

In this issue of *Joule*, Dongmin Im and coworkers from Samsung in South Korea describe a prototype lithium-O_2 battery that reaches ~700 Wh kg^{-1} and ~600 Wh L^{-1} on the cell level. They cut all components to the minimum to reach this value. Difficulties filling the pores with discharge product and inhomogeneous cell utilization turn out to limit the achievable energy. Their work underlines the importance of reporting performance with respect to full cell weight and volume.

Mobile energy sources are powering modern society. Lithium-ion batteries were key drivers for the recent portable electronics revolution but are reaching the limits of possible energy storage per unit mass.[1] With the more widespread drive to adapt them into large-scale applications like electric vehicles, properties like sustainability and cost become ever more important.[2] Research into alternative technologies is hence needed to serve these additional requirements. Among the few options, metal-air batteries have attracted tremendous attention because they theoretically hold a much higher energy per unit mass than current Li-ion batteries.[1,3,4] They use lithium metal (but variants with sodium or potassium also exist) at the anode and oxygen—drawn from air—at the cathode. In the Li-O_2 cell the active material at the cathode is Li_2O_2, which forms according to electrochemical reaction $O_2 + 2\ e^- + 2\ Li^+ \leftrightarrows Li_2O_2$. This way they avoid expensive and toxic cobalt as used in current lithium-ion batteries. However, akin to many so-called "beyond-intercalation battery chemistries," reporting performance metrics that are meaningful in comparison to established battery chemistries is tricky.[5,6] Numbers based on the active material alone, as done for Li-ion materials, is prone to hugely overemphasize the gain in energy with the new battery chemistries. Work such as that now reported by Im and co-workers[7] will provide more realistic views on the achievable performance.

Li-O_2 batteries with exceptionally high energies have been claimed many times before. Numbers were based on extraordinarily high capacities per carbon electrode mass, which in some cases reached several 10,000 mAh•g_C^{-1}.[5] Such values compare superficially very favorably to ~100–300 mAh•g^{-1} of active intercalation material in Li-ion batteries. However, to judge true electrode performance, all active and inactive components need to be included. By doing so, Im and co-workers[7] achieve a cell-scale specific energy of 700 Wh•kg_{cell}^{-1}, considering the mass of all cell components of the folded cell structure. Decisive for capacity is the degree with which the initially electrolyte-filled pores of the electron-conducting porous electrode can be filled with Li_2O_2 (Figures 1A and 1B). This can only be achieved if nanopores are filled uniformly across the cathode by a large fraction with active material (Li_2O_2).[5] To achieve high specific cell energies both microscopic limitations[4,8,9] and parameters defining the uniformity on a macroscopic (cell) scale need to be identified.

Given its central importance for capacity and rate capability, the way that Li_2O_2 forms in the porous cathode has been subject to intensive investigations over more than a decade.[3,8,9] It is now widely accepted that Li_2O_2 may form via either a surface or solution mechanism, which results in either conformal coating of the pore surface

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